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by

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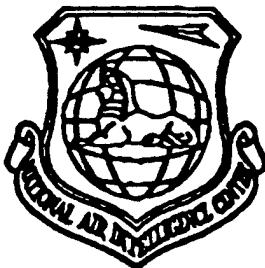
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ATMOSPHERIC ATTENUATION OF COMMON APPLIED LASERS

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Abstract: A survey of the atmospheric attenuation
properties of usually applied laser (GaAs, YAG, HF,
DF, and CO_2) is given. From an analysis of the
results of absorption and scattering processes
produced by the interaction of atmospheric medium
and laser radiation, comprehensive comparisons of
transmission property are performed. Lastly, the
optimum applied environment of every laser is
indicated.

1. Introduction

Essentially, research on laser propagation through the
atmosphere involves studying the interaction of the atmospheric
medium and laser radiation, i.e., scattering and absorption of
radiation by the medium, as well as studying how the laser
changes its own properties owing to atmospheric effects. Under
particular conditions, however, radiation can also change the
properties of the atmosphere, which can possibly lead to
nonlinear effects. So it is vitally important to get insight

into the regularities of these processes so that laser engineering can be appropriately designed and brought into full play.

This paper gives an analysis of the atmospheric attenuation properties of some commonly used lasers (GaAs, YAG, HF, DF, and CO_2, etc.) and introduces the research achievements achieved in China in this field. As for the effect of atmospheric turbulence on these lasers, it will be discussed in another paper.

2. Fundamental Process of Atmospheric Attenuation

Normally, transmittance τ of homogeneous radiation in the uniform atmosphere can be described using Lambert's law as follows:

$$\tau \equiv \frac{I}{I_0} = \exp(-\beta L) \tag{1}$$

where I_0 and I, respectively, are the initial intensity of laser radiation, and the intensity of laser radiation after propagating over a distance L; β is attenuation coefficient. Based on different mechanisms of scattering and absorption, β can be written as

$$\beta = \sigma_m + k_m + \sigma_a + k_a \tag{2}$$

where σ is scattering coefficient; k is absorption coefficient; the subscripts m and α, respectively, are molecules and aerosol particles. The contribution of all the foregoing unit factors to the attenuation, respectively, is discussed as follows:

1. Molecule Scattering

The scattering of incident light by gas molecules is also called Rayleigh scattering. The scattering coefficient σ_m is determined by the following formula:

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$$\sigma_m = \frac{8\pi^3(n^2-1)^2}{3Ng\lambda^4}\left(\frac{6+3\delta}{6-7\delta}\right) \tag{3}$$

where n is the refractivity of air; Ng is number of molecules per unit volume; λ is wavelength; δ is depolarizing factor. According to the latest measurements, $\delta=0.035$. At various altitudes below 100km, the atmospheric Rayleigh scattering coefficient can be approximately written as[1]:

$$\sigma_m = 4.56\times10^{-22}Ng\left(\frac{0.55}{\lambda}\right)^4 \quad (km^{-1}) \tag{4}$$

where λ is calculated in μm, while Ng is calculated in cm^{-3}. At sea level, $Ng=2.55\times10^{-9}cm^{-3}$ under standard atmospheric conditions. Table 1 lists the σ_m value of several wavelengths under standard atmospheric conditions at sea level. It can be seen from Eq. (3) and Table 1 that molecule scattering is significant only at the visible light band and ultraviolet band of short wavelength, while above 1.06 μm, it can be ignored.

TABLE 1. Molecule Scattering Coefficient of Several Lasers (Under Standard Atmospheric Conditions at Sea Level)

$\lambda(\mu m)$	0.55	0.9	1.06	2.91	3.80	10.6
$\sigma_m(km^{-1})$	1.162×10^{-2}	1.62×10^{-3}	8.43×10^{-4}	1.50×10^{-5}	5.10×10^{-6}	8.43×10^{-8}

2. Molecular Absorption

Molecular absorption primarily occurs in the infrared laser with a longer wavelength, as well as more or less in GaAs and YAG lasers. Nevertheless, compared with aerosol attenuation, it is normally a negligible variable. This absorption chiefly involves spectral line absorption and spectral band absorption.

Spectral line absorption is usually a kind of resonant absorption, which is closely related to spectral properties such

as spectral line position, absorption power, and spectral line half-width.

Spectral band absorption is also referred to as continuous absorption in the case when the absorption lines are more or less concentrated, which is associated with the wings on both sides of the absorption line or pressure-related frequency band. In addition, the continuous absorption of vapor is also associated with the water molecule polymers.

Either the spectral line absorption or the spectral band absorption is a function of wavelength drastic change and therefore, must be studied separately according to specified wavelengths. Besides, since each laser can operate at multiple spectral lines, it is not possible to discuss line by line in this paper. Our following discussion will be focused on a particular spectral line with higher transmittance and better propagation properties in the foregoing lasers.

Molecule absorption in CO_2 laser is mainly resonant line center absorption from the atmospheric CO_2, and continuous absorption of vapor, yet O_3 absorption at 9.4μm band also cannot be ignored. Reference[2] presents a universal formula for absorption coefficients of various spectral lines of CO_2. The P_{20} line can be simply written as[3]:

$$R_{CO_2} = \frac{6.87 \times 10^5 x}{Q(T)T^{0.42}} \exp\left(7.44 - \frac{2233}{T}\right)$$
$$(\text{km}^{-1})$$

(5)

where x is the mixing ratio of CO_2; T is absolute temperature (K); Q(T) is partition function. We found that the R_{CO2} of the P_{20} line and T are in the following relationship in the range T=290-365K:

$$R_{CO_2} = 6.979 \times 10^{-13} T^{5.395}$$
$$(\text{km}^{-1}\text{atm}^{-1})$$

(6)

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The correlation coefficient of logR and logT can be as high as 0.993. Despite the fact that the power exponential of temperature is different from the theoretical value, still, Eq. (6) conforms to the calculations given in reference[4], while the result in Eq. (5) seems to be understated.

The continuous absorption coefficient of CO_2 laser by the vapor is related not only to the vapor partial pressure P_H, but also to factors, including total environmental pressure P, temperature T, as well as self-broadening factor and externally broadening factor. Generally, it can be expressed in the following formula:

$$R_{H_2O} = A p_H [p_H + v(P - p_H)]$$

(7)

where A is a particular constant; v is the ratio between self-broadening factor and externally broadening factor. McCoy[5] derived $A = 8.38 \times 10^{-4}$, and $v = 1/194$ through laboratory measurements. However, recent studies suggest that both A and v are a function of temperature. According to optical sound measurements conducted by Wu Jihua et al., the following can be derived for the P_{20} line:

$$A = \frac{0.267}{T} \exp \left[4000 \left(\frac{1}{T} - \frac{1}{296} \right) \right]$$

(8)

$$v = 3.4 \times 10^{-3} \exp \left[7000 \left(\frac{1}{296} - \frac{1}{T} \right) \right]$$

(9)

Calculations show that when T=296K, the result in reference[6] is in close agreement with the result given in reference[5]. In addition, in an environment with less vapor P_H is less than or approximately equal to 10Torr and lower gas pressure (P~670Torr), whether or not the result in reference[6] is applicable is to be discussed. In fact, the attenuation coefficient that Hanley et al.[7] derived through actual measurements in similar environments is approximately one order of magnitude larger than in the foregoing formula. These facts demonstrate that there may be some uncertain factors in indoor vapor absorption simulation measurements.

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Among the effective absorptive molecules of Df laser are: H_2O, N_2, N_2O, CH_4, HDO, and CO_2, etc. For the $P_2(8)$ line with better transmittance, N_2 and H_2O absorption is predominant, while N_2 absorption is continuous absorption. Bunch[8], based on a very large number of experiments, proposed the following empirical formula:

$$R_{N_2} = 5.67 C_{N_2} \frac{P^2}{T} \quad (km^{-1}) \tag{10}$$

where C_{N_2} is a coefficient associated with wavelength. For 3.801μm, $C_{N_2} \approx 0.087$. Normally, R_{N_2} can simply be selected.
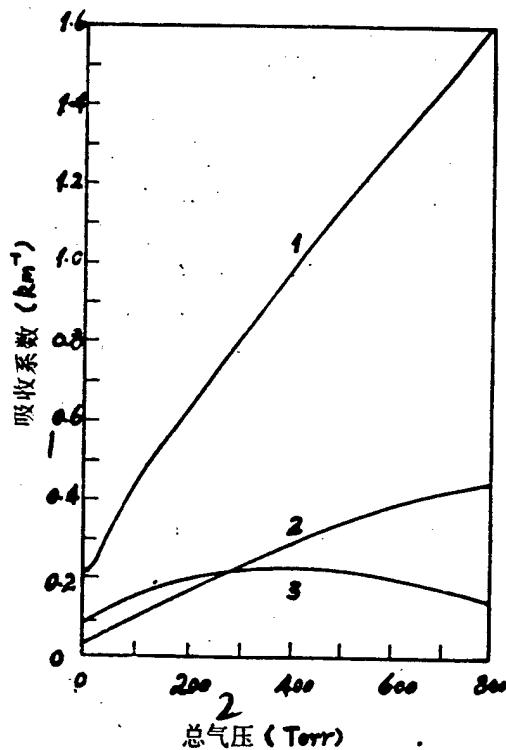

Fig. 1. Vapor absorption coefficients of HF laser $P_2(8)$ line in different environments KEY: 1 - absorption coefficient 2 - total gas pressure

Vapor absorption involves spectral line absorption and continuous absorption. Spectral line absorption is fairly weak under summer standard atmospheric conditions in mid-latitude

regions. The vapor spectral line absorption coefficient at sea level is approximately 0.003 km^{-1}. In the early studies of vapor continuous absorption, the role of HDO was generally ignored so that the absorption value thus measured appeared understated compared with recent studies.

Based on a field survey of several spectral lines of the DF laser, Hanley et al.[7] found that the actual measurements roughly conformed to the value calculated under the HITRAN model, while the result of the $P_2(8)$ line was in close agreement with it. According to the data presented in reference[7], it was found that the following formula can be derived, in approximate terms:

$$R_{H2O} = 2.48 \times 10^{-3} p_H$$

(11)

This formula is suitable for a constant-temperature environment. At P_H=14.3Torr, this formula offers R_{H2O}=0.035km^{-1}, which conforms to the indoor measurements of White et al.[9] but twice as large as the earlier calculations made by Burch et al.[8].

Through actual measurements at a visibility of 8km in Dalian, Wu Jihua et al.[10] derived τ=0.9 (β=0.105km^{-1}) at p=22.1Torr, which completely conforms to the calculated value which takes the absorption of all molecules into account. However, this result appears a little higher if aerosol attenuation is counted.

The transmission spectral line of HF laser is located in the 2.7μm strong absorption band of H_2O and CO_2; ozone and methane, though weak, are also worth noticing. Of all the six bands of HF laser, the transition at a high vibrational energy level is accompanied by higher atmospheric transmittance. At present, however, of the many spectral lines capable of realizing high power continuous output, the $P_2(8)$ line displays the highest transmittance, while the other spectral lines have entirely different transmittance with the maximum difference reaching

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hundreds of times.

Also, molecular absorption in the HF laser can be estimated theoretically using the line-by-line calculation technique, or a parameterized empirical formula similar to Eq. (6) can be established on the basis of laboratory measurements. However, for lack of knowledge of the dependence of the self-broadening coefficient and the externally broadening coefficient on temperature and pressure, the foregoing technique can only be applied in particular conditions.

The theoretical calculation made by McClatchey et al.[11] shows that the molecule absorption coefficients of the $P_2(8)$ line at sea level in summer and winter in mid-latitude regions, respectively, are $1.424km^{-1}$ and $0.221km^{-1}$ (vapor content is 14cm and 3.5cm, respectively based on precipitation thickness calculation).

Watkins et al.[12] found that the absorption coefficient measured in the laboratory roughly agrees with the value derived based on Voigt linear calculation. Fig. 1 shows the vapor absorption coefficient of the $P_2(8)$ line that they calculated on account of the parameters measured under specified conditions. It is known then that the attenuation of the $HFP_2(8)$ line is extremely small in a low temperature environment several kilometers above the ground.

While Wu Jihua et al.[10] derived $\beta=1.66km^{-1}$ of the $P_2(8)$ line in the atmosphere with a temperature 24^0C, visibility 5km, and vapor 12.4Torr, which completely conforms to the summer hazy weather pattern in the mid-latitude regions as described in reference[11], and also is very close to the calculations made under similar conditions in reference[12].

3. Aerosol Attenuation

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The attenuation of laser beams by the atmospheric aerosol covers scattering and absorption. It can be calculated through particle scattering theory as long as the aerosol properties, such as concentration, scale distribution, and complex refractivity exponent, are known. Generally speaking, such calculations can reach better accuracy, but due to the great variation of the aerosol properties in time and place, the attenuation can only be estimated in accordance with a particular pattern, which inevitably will lead to certain deviation of the estimated value of the actual atmospheric attenuation.

Theoretical analysis[13] indicates that the attenuation coefficients of the same-category land or sea aerosol can be different if their spectrum shape is different; similarly, the attenuation coefficient also can be different for aerosols with the same spectrum shape but different category.

These two features have a even more remarkable effect on lasers with long wavelength, because most of the particles are probably located in a range with a small value of $x-2\Pi\alpha$, i.e., close to the Rayleigh scattering zone, where aerosol attenuation is extremely sensitive to particle scale and refractivity exponent. For instance, the attenuation coefficient at $10.6\mu m$ wavelength may change by approximately one order of magnitude because of the difference in spectrum shape and refractivity exponent.

Consequently, it would be unreasonable to describe such laser radiation attenuation coefficient with atmospheric visibility alone, which can only reflect aerosol concentration. However, this approach is applicable for lasers with a short wavelength, and especially accurate for sea aerosol. As a matter of fact, the foregoing conclusion has been confirmed by many experimental measurements.

Since visibility measurement is much simpler than the measurement of aerosol spectrum shape and refraction exponent, the following empirical pattern is often used in engineering application to estimate the aerosol attenuation coefficient[1]:

$$\beta_a = \frac{3.912}{V_M}\left(\frac{0.55}{\lambda}\right)^q \quad (km^{-1}) \tag{12}$$

where $q=0.585 V_m^{1}/3$ when $V_M \leq 6km$; $q=1.3$ when the average visibility V_M is a visibility distance in the atmosphere (km); λ is wavelength (µm). It was reported that q can change from 0.12 to 2.3[14], yet Wu Jihua et al.[15], based on a series of experiments with 1.06 and 0.6328µm wavelengths, which were conducted, respectively, in Shanghai and Hefei, came to a conclusion which basically conformed to Eq. (12). We also confirmed that Eq. (12) is applicable through the measurement of 0.9µm radiation in Qingdao and Huangshan.

The measurement of 10.6µm is much more complex. The authors of reference[3] derived q≈0.634 in Hefei. Or, by rewriting Eq. (12) as

$$\beta_a = A/V_M \tag{13}$$

$A=0.6 km^{-1} (V_M \geq 2km)$ can be obtained, whose root-mean-square deviation is 0.27. It can be expected that the value of A will vary from region to region.

The aerosol attenuation with DF and HF lasers was studied theoretically[11], but no detailed report was issued concerning systematic experiments and measurements. If the scale distribution of particles does not change in a certain range of visibility, then the value of A can be calculated approximately through interpolation of the theoretical value as A(3.8µm)≈0.676 and A(2.91µm)≈0.874, respectively.

TABLE 2. Values of A for Several Wavelengths
(V_M ≤ 1km)

$\lambda(\mu m)$	0.53	0.63	0.9	1.06	10.6
$A(km^{-1})$	2.46	3.18	3.3	3.06	2.1

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Fog attenuation is very critical, and its attenuation coefficient also can be approximately calculated in accordance with Eq. (13). Table 2 lists values of A for several wavelengths, measured at the Anhui Institute of Optics and Fine Mechanics in Qingdao and Huangshan; the values given in this Table vary over roughly the range ±(10-20)%. Fig. 2 shows the average measurement results of three wavelengths obtained at a visibility less than 1km in the foregoing regions; the straight line is calculated based on the data from Table 3. These data show that the CO_2 laser has a better fog-penetrating property compared with other radiations.
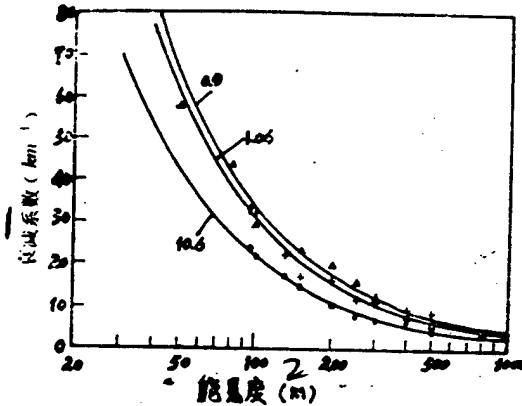

Fig. 2. Comparison of three radiations in fog attenuation

It is to be noted that owing to different fog properties in different regions, the degree of attenuation can be different. In the Chongqing region, for example, the average 10.6µm attenuation coefficient in winter is around 10 times lower[16] than the foregoing data, while in the Soviet Union and Federal Republic of Germany, similar or even identical values were obtained. Hence, we should be cautious when applying the data in Table 2.

Generally, the rain attenuation with laser radiation is weaker than that of fog at the same visibility, because rain drops are relatively large (normally 0.2-2mm) and possess extremely strong forward scattering effects. In principle, like haze attenuation, the rain attenuation can also be calculated according to the particle scattering theory; but since the scale spectrum of a raindrop is the function of rain power, it therefore can be anticipated that rain attenuation will also be directly related to the rain power. Experiment shows that the relationship between the

attenuation coefficient β_R and rain power is as follows:

$$\beta_R = aJ^b (km^{-1}) \qquad (14)$$

where α and b are fitting parameters; j is calculated in mm/hr.
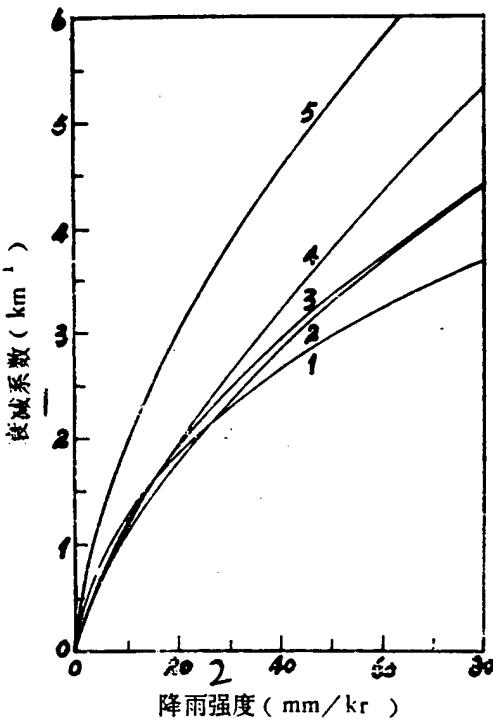
Fig. 3. Relationship between attenuation coefficient and rain power
KEY: 1 - attenuation coefficient 2 - rain power

Curves 1-4 in Fig. 3 show calculations made at 10.6μm by several authors[17,18]. it can be seen from the figure that all the

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curves are roughly identical when J≤20mm/hr, while when
J>20mm/hr,
curve 1 is obviously too large, and curve 4 is obviously too
small; the other two curves basically remain consistent at all
powers.

Similar relationships can also be found at other
wavelengths. This is because all the wavelengths--from visible
light to 10.6μm--are much smaller than the radius of a raindrop,
and the attenuation at different wavelengths should be roughly
identical.

The measurement result obtained by Bisyarin et al. suggests
that in a drizzle, the difference between the attenuation
coefficients of 0.63 and 10.6μm usually ranges from 10% to 20%.
Using a ruby laser, Shipley et al.[19] measured $\alpha=0.16\pm0.04$, and
$b=0.74\pm0.12$, which are slightly lower than the average
measurement result with 10.6μm.

Snow attenuation has not been solved so far in theory.
Generally speaking, with the same water content, snow attenuation
is higher than rain attenuation but lower than fog attenuation.
Experimental studies indicate that Eq. (14) is also suitable for
snow; curve 5 in Fig. 3 is one of the examples[20].

3. Comparison of Commonly Used Lasers in Atmospheric Attenuation

Based on the foregoing analysis of monofactors, let us make
a comparison among commonly used lasers in terms of their
attenuation properties. Fig. 4 shows the relationship between
the attenuation coefficient and visibility of five kinds of
lasers under general weather conditions at sea level in mid-
latitude regions. Among other things, the summer conditions are:
$p=760$Torr; $P_H=14.2$Torr; $T=294$K; while the winter conditions are:
$p=763.6$Torr; $P_H=3.3$Torr; $T=272.2$K. The content of CO_2 was taken

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as 330ppm per year.

It can be seen from Fig. 4 that the $P_2(8)$ line of the DF laser has the best propagation property, while for the $P_2(8)$ line of the HF laser, its propagation property seems to be worst in summer but greatly improves in winter.

As far as the most commonly used lasers, i.e., 10.6 and 1.06μm lasers are concerned, the former displays its supremacy only at a poor visibility, yet becomes inferior to the YAG laser with an increase in vapor content and visibility (V_M>5km in summer, and V_M>10km in winter). The attenuation of the GaAs laser is similar to that of the YAG laser, but a bit higher than that of the latter.
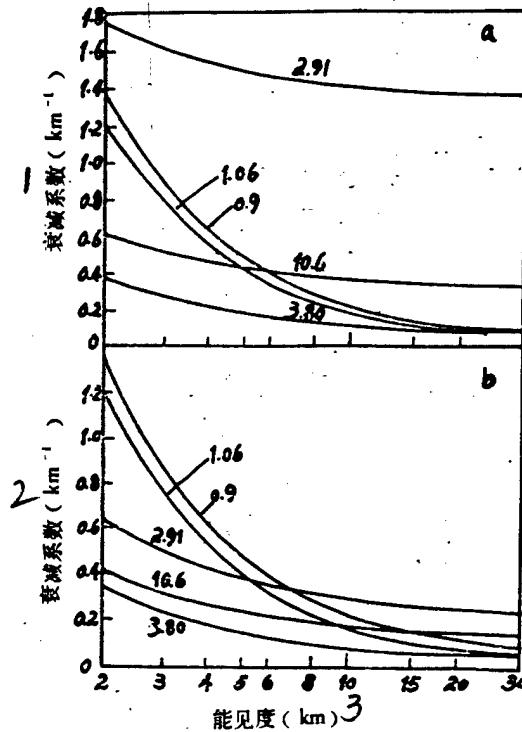
Fig. 4. Comparison among commonly used
lasers in atmospheric attenuation
a-summer at mid-latitude; b-winter at
mid-latitude
KEY: 1 - attenuation coefficient
   2 - attenuation coefficient
     3 - visibility
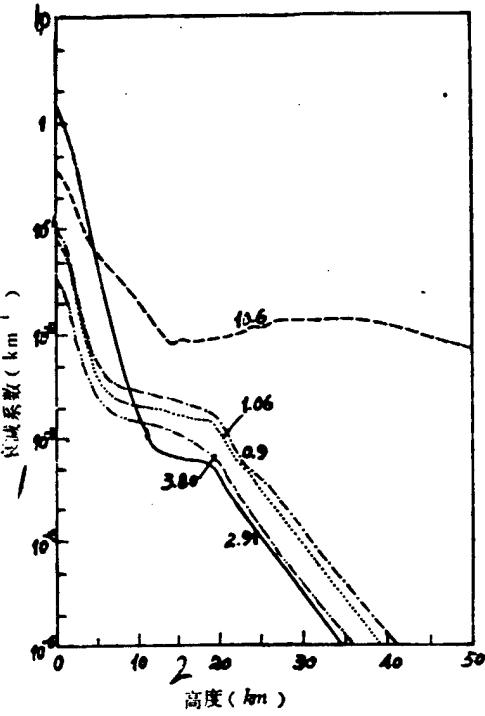
Fig. 5. Altitude distribution of attenuation
coefficients of five kinds of lasers (in
typical summer sunny atmosphere at mid-latitude)
KEY: 1 - attenuation coefficient 2 - altitude

The laser slant attenuation can be dealt with only using the
theoretical calculation based on a particular atmospheric pattern
because of difficulties in actual measurements. By using the
target diffuse reflection technique, the back-scattering
technique, and the solar radiation technique, Wu Jihua et al.[15]
worked out actual measurements of the 1.06μm laser slant
attenuation, as well as theoretical calculation using the
equivalent horizontal distance conversion method.

We measured the YAG laser slant attenuation on an aircraft
in Xinxiang, and the measurement results showed that both the
measured and converted values are basically the same even with
different techniques.

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Theoretical analysis suggests that the attenuation of most lasers in slant propagation occurs primarily in the range from the ground to an altitude approximately of 3km. For instance, at the ground horizontal visibility 5km, the vertical transmittance of the 1.06μm laser within this range is around 0.5, while its transmittance through the entire atmosphere is 0.49, i.e., the difference is only 0.01. This is because the atmospheric aerosol is distributed mainly in the atmosphere below 3km, and the vapor content above this altitude is also greatly reduced. The only exception is the 1.06μm laser slant attenuation. Because the CO_2 molecules as one of the major attenuation factors are fully mixed in the atmosphere, its mixing ratio at the altitude 20km is still much the same as on the ground.

To present a quantitative concept, Fig. 5 shows the altitude distribution of the attenuation coefficients of five lasers in the summer sunny weather conditions (V_M=23km) at the median latitude. It can be seen from this Figure that under such weather conditions, the CO_2 laser displays the worst propagation property, while the HF laser, though suffering from the largest attenuation at low altitudes, will become the best wavelength when reaching above 10km in altitude. The other three lasers have no much difference in this aspect.

The foregoing conclusion is also suitable for winter conditions or poor ground visibility conditions (V_M-5km), because the aerosol concentration at high altitudes basically has nothing to do with the ground visibility. But it is certainly an exception in the cloud and precipitation conditions, which are not included in the discussion in this paper.

To summarize, we hereby propose several conclusions from the angle of the atmosphere as follows:

1. The CO_2 laser, with its best fog-penetrating property, is suitable for bad weather (V_M≤5km) conditions but inferior to

other lasers in dry weather and at high visibility, or at high
altitudes.

2. The DF laser is superior to all other lasers in
propagation property, and is slightly inferior to the HF laser
only at an emission altitude more than 10km.

3. The HF laser is most suitable for dry regions or high
altitude environments. It may become the best wavelength in high
altitude applications owing to its shorter wavelength among
infrared lasers, better beam quality, high conversion efficiency
and low cost.

4. The YAG and GaAs lasers possess a moderate propagation
property and therefore, are expected to have broad prospects in
general applications.

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